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Examination of a Wear-Reducing Muzzle Device

by William S. de Rosset and Jonathan S. Montgomery

ARL-TR-6557 August 2013

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ARL-TR-6557 **August 2013**

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
August 2013

2. REPORT TYPE
Final

3. DATES COVERED (From - To)
1 October 2012–30 June 2013

4. TITLE AND SUBTITLE
Examination of a Wear-Reducing Muzzle Device

5a. CONTRACT NUMBER
ORISE 1120-1120-99

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
William S. de Rosset and Jonathan S. Montgomery

5d. PROJECT NUMBER
AH84

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: RDRL-WMM-F
Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-6557

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Tests have been conducted on a device intended to reduce muzzle wear. The device is made of a hard, wear-resistant material attached to the muzzle end of the gun tube. The bore diameter of the device is slightly less than the bore diameter of the gun. The intent is to reduce yawing motion of the bullet inside the gun tube and increase accuracy. The tests showed that the constriction reduced the muzzle velocity and increased bullet dispersion. Hexagonal boron nitride was used in an attempt to reduce frictional forces between the bullet and gun tube and increase muzzle velocity. Although this was not achieved, the amount of gun tube fouling appeared to be reduced with its use.

15. SUBJECT TERMS
muzzle wear, M240 barrel, gun precision, hexagonal boron nitride

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Jonathan S. Montgomery
Unclassified	Unclassified	Unclassified	UU	32	19b. TELEPHONE NUMBER (*Include area code*) (410) 306-0868

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures

List of Tables

Acknowledgments

The authors gratefully acknowledge the excellent work that Tom Puckett and his crew did in the firing tests of the M240B barrels. We also acknowledge Robert Keppinger for the barrel bore measurements, Bradley Klotz for the microscope work, and Ron Anderson for reducing the target hit location data.

1. Introduction

Gun barrel wear and erosion come about as the result of a complex interplay among thermal, chemical, and mechanical effects. The removal of gun tube material by mechanical wear can be caused from the interaction of the moving bullet and gun tube wall. However, the amount of material removed may also depend on the temperature of the metal parts and the softening of the gun tube material via a chemical reaction with the propellant gasses. Chemical erosion can occur through hydrogen embrittlement and subsequent sloughing off of gun barrel material. This and other chemical reactions can be accelerated as a result of the high pressure and temperature of the propellant gasses, leading to further loss of gun barrel material. If the bullet loses its seal (obturator), then hot propellant gasses may blow past the bullet, "washing" barrel material away.

Recent tests of an M249 machine gun barrel made from Ultimet,* a cobalt−chromium alloy, have largely separated the effects of mechanical wear from thermal and chemical effects (*1*). Ultimet is a refractory metal that is capable of withstanding high temperatures and a chemical attack. Consequently, most of the wear observed during the tests is due to the mechanical interaction of the bullet with the gun barrel surface. Figure 1 shows representative data from these tests. In this figure, the inner diameter of the barrel at the land location is plotted versus the axial position. The rear face of the tube is at 0 mm and the muzzle is at 464 mm. These measurements were taken after a given number of rounds were fired through it, as indicated in the figure. There is virtually no loss of gun barrel material near the breech, where chemical and thermal effects are expected to be greatest. However, toward the muzzle end of the gun barrel, the loss of material (i.e., increase in the inner diameter of the gun barrel) increases with the number of rounds fired.

The type of muzzle wear reported in (*1*) is well known in large caliber gun tubes (*2*). Muzzle wear is responsible for increased dispersion, because the trajectory of the projectile is determined to some extent by its interaction with the gun tube during the last few calibers of travel. If there is excessive muzzle wear, then the possibility exists that propellant gasses blow past the projectile in an uneven way, producing a net lateral force on the projectile as it leaves the muzzle. There may also be a loss in muzzle velocity due to gun tube wear, and this is not restricted to just wear at the muzzle. Remedies cited in (*2*) to overcome muzzle wear include increasing the load carrying capacity of the rotating band of the projectile or increasing the wear resistance of the cannon bore.

With exceptions, such as sabot-launched armor piercing rounds, small arms projectiles have no rotating bands. There is metal-to- metal contact between the projectile and barrel the entire length of the bore. It can be argued that the greatest mechanical wear occurs for the highest

*Ultimet is a registered trademark of Haynes International, Inc.

projectile velocity and spin rate. The bullet starts at rest and is accelerated down the gun tube, increasing both its velocity and spin rate. Under this hypothesis, the greatest mechanical wear will occur at the muzzle end of the gun tube.

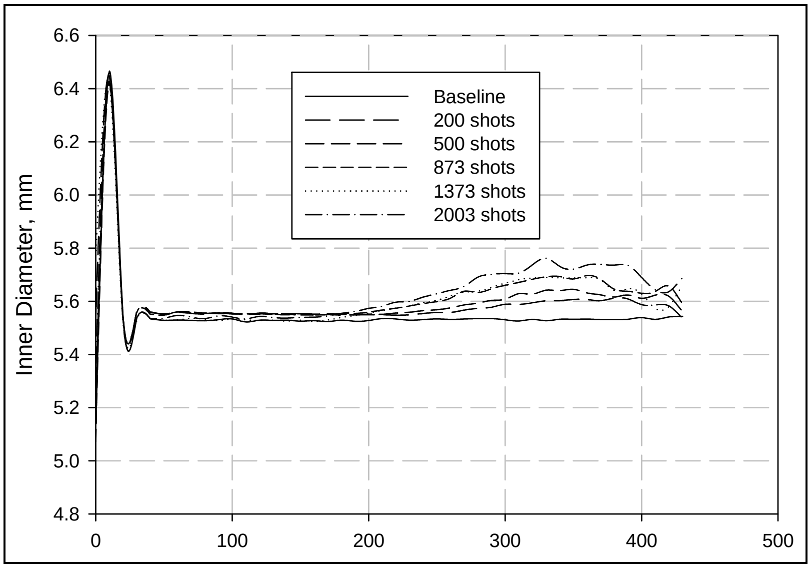

Figure 1. Results of M249 machine gun barrel wear tests (*1*).

This concept is supported by the results shown in figure 1. The gradual increase in-bore diameter near the muzzle is simply a result of the erosion of the lands. The diameter shown in figure 1 increases relatively quickly to the groove diameter, at which point the land is completely removed. The increase in barrel diameter becomes much slower at that point. In fact, the bore diameter appears to decrease near the muzzle. This is ascribed to the buildup of copper on the bore surface.

Results in (*1*) suggest that the use of refractory metal liners in small caliber weapons can extend the service life of the barrel. However, although this type of material can resist both chemical and thermal attack, it cannot, in general, overcome the abrasive effects of metal-to-metal contact for a large number of rounds. The use of different materials at different locations in the gun tube is clearly indicated. Near the breech, a refractory metal can be used to resist the high-chemical activity, pressure, and temperature. Near the muzzle, where the temperature and pressure are lower, a wear-resistant material can be used.

Such a muzzle device, denoted as the de Rosset−Montgomery (DM) device, is detailed in (*3*). An embodiment of this device is shown in figure 2. It is simply a high-strength metal part that screws onto the end of the barrel in the same way the flash suppressor is attached. In a more advanced design, ceramics can also be considered as the material of choice. Two dimensions are also shown in this figure. L is the length of gun tube that is removed and replaced by the DM device, and D is the bore diameter. There is no rifling in the DM device.

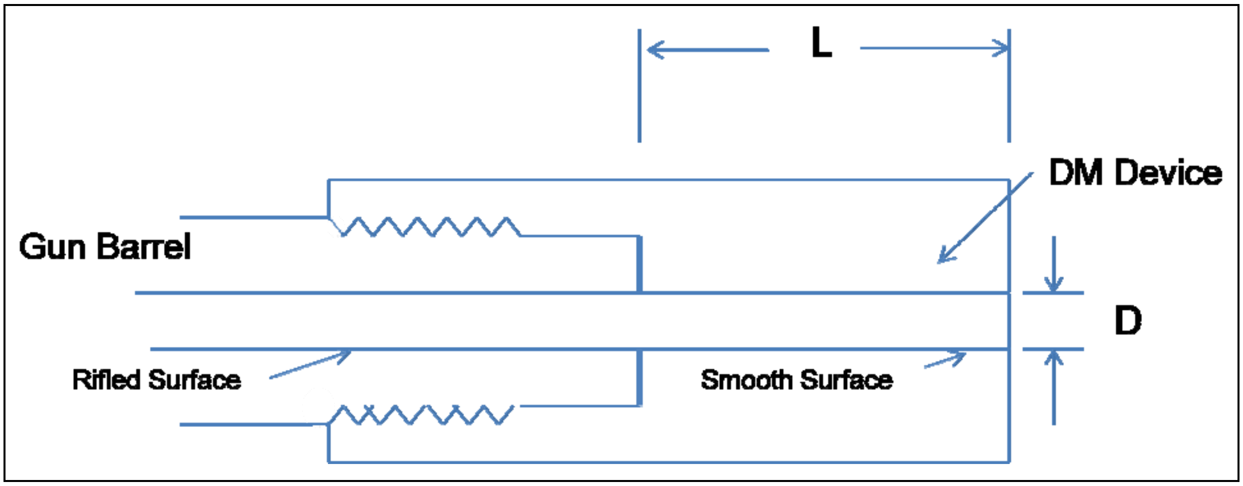

Figure 2. Sketch of the DM device.

If muzzle wear can be avoided with the DM device, then the dispersion of the fired rounds due to muzzle wear should not increase as the end of the barrel's service life is approached. Consequently, over the life of the barrel, it will shoot more precisely. Of course, there should be little difference between a brand new standard barrel and one with the DM device. Note that muzzle wear is only one source of rifle imprecision and reducing it can help only so much. The appendix is a summary of other sources of rifle imprecision. (Note that we use the term "precision" here; the word "accuracy" has also been used for dispersion effects.) Due to the expected wear of the barrel near the DM device after a number of firings, it may be that the projectile enters the device in a slightly cocked or off-center orientation. Having D equal to the original bore diameter (groove location) would help to straighten out the projectile. If the diameter D is slightly less than the bullet diameter, there will be a "choke" effect that may modify the bullet's exit velocity and spin rate. However, it would also ensure that the projectile left the gun tube along a trajectory parallel to the axis of the DM device. (The overall gun tube motion may affect the aim point.) For this reason, it was believed that the DM device had the potential to increase the accuracy or reduce the dispersion of the weapon.

One of the primary questions concerning the DM device is what dimensions (the values of L and D) should be selected for optimal performance. If L is too large (or D is too small, or both), there may be an adverse effect on the speed of the bullet. If L is too short (or D is too large, or both), the DM device may not be effective in straightening out the bullet's trajectory.

A second question is the material to be used for the DM device. The main criterion for this material is resistance to mechanical wear. For the initial tests, Maraging 300 steel, hardened to 60 Rockwell Hardness C Scale (HRC), was chosen for reasons of cost and ease of fabrication. A ceramic could also be considered as a liner to the DM device. The short length of ceramic liner would avoid the problems experienced in the past with maintaining tolerances over an extended length of gun tube. The fact that the DM device is at the muzzle also avoids some of the problems experienced with ceramic tubes and liners used the full length of the gun tube (i.e.,

near the breech where pressures are high). Finally, because the DM device has no rifling, the fabrication of a short liner would avoid problems, such as machining lands and grooves in a very hard material or lining up the grooves in the extension with the grooves in the barrel itself.

To lessen the impact of the small diameter of the DM device on the bullet's velocity and spin, a high-pressure lubricant was sought that could be used to reduce friction between the bullet and gun barrel wall. In researching the application of lubricants to bullets, a patent was found that covered this topic (*4*). The lubricant discussed in reference 4 is hexagonal boron nitride (HBN), sometimes referred to as "white graphite" because of its laminar morphology and excellent lubricating properties at high pressure and temperature. Calkins (*4*) claims that applying a thin coating of HBN to each bullet will result in reduced friction, higher muzzle velocity, and greater accuracy. Also, Calkins (*4*) claims that the use of an HBN bullet coating will result in filling cracks and grain boundaries in the bore surface via a burnishing action, thereby reducing barrel wear and providing a smooth surface. Calkins (*4*) also states that a HBN coating that is too thick will result in erratic results and no velocity increase. No critical coating thickness values were provided, however.

Boyle et al. (*5*) have attempted to measure the reduction in friction between the bullet and bore for several lubricants. Hexagonal boron nitride was the only bullet coating that that was able to reduce friction for each of three different types of bullets studied. The amount of reduction varied from less than 1% up to 15%, depending on the type of bullet. (The authors noted that their approach was unable to separate the engraving force from the frictional force.)

There are several questions being addressed by this work. The first is to determine if the bullet will survive a decrease in-bore diameter near the muzzle. Given that the bullet exits the muzzle intact, what will be the effect of the DM device? That is, will use of the device increase, maintain, or decrease the baseline values of velocity and accuracy? If there is a significant reduction in either the velocity or accuracy, then the long term benefits of the device will be negated. The performance of the DM device will depend on the choice of L and D to some extent. These values can be optimized once the feasibility has been established. Also, to what extent will the use of hexagonal boron nitride affect the muzzle velocity of the M240B machine gun barrel? Use of HBN may be critical to reducing the friction between the DM device and the bullet.

The work was divided into three phases. The first was to establish the baseline dispersion and velocity performance for four individual M240B barrels. Both coated and uncoated bullets were used. The second phase was to modify one of these barrels to accept a DM device. Two particular DM designs were chosen for testing. The goal of this phase was to see the effect of the DM device and select a design for tests in the third phase. Although only a limited amount of testing was done in this phase, the results pointed to a reasonable design. This design was used in the third phase. Firing tests with the M240B barrel with the DM device were conducted and compared to the baseline numbers. In this phase, rather than coat the bullets, the lubricant was

applied to the barrel itself. The next section describes the experimental approach used in each phase of the work. Results, presented in section 3, will also be organized according to phase. Section 4 discusses the results, and section 5 provides a summary of the work.

2. Experimental Approach

2.1 Phase 1

In anticipation of variation in the performance of standard-production M240B machine gun barrels, four of these barrels were procured from FN Manufacturing, Columbia, South Carolina. The redundant tests allowed an estimate of the barrel-to-barrel variation. All firing tests were conducted at a 100 m range (307 ft from the gun muzzle to the target). The 100 m range (307 ft from the gun muzzle to the target) was used for all the tests. Paper targets backed by plywood were used to score the bullet impact locations. Before the tests, each bore diameter was measured with a Bore Erosion Measurement and Inspection System (BEMIS).

The test matrix for firing these barrels is shown in table 1. Ten warmer shots, designated by W in table 1, were fired through each barrel. This allowed the aim point to be adjusted until the shot group was in the middle of the target. The warmer shots were followed by three groups of 30 rounds each to measure dispersion and velocity (D and V, respectively, in table 1). The same number of shots was used for both the standard ammunition and the coated ammunition, with a total of 800 shots being fired. A stepper trigger was used to fire the bullets one at a time. For the dispersion tests, the impact location of each shot was noted on a separate piece of paper. Later, each target impact was identified by shot number. There was some uncertainty in impact location when multiple shots hit the same general area.

Table 1. Firing test matrix for phase 1.

Barrel No.	**Standard Ammunition**				**Coated Ammunition**			
1	10 W	30 D/V	30 D/V	30 D/V	10 W	30 D/V	30 D/V	30 D/V
2	10 W	30 D/V	30 D/V	30 D/V	10 W	30 D/V	30 D/V	30 D/V
3	10 W	30 D/V	30 D/V	30 D/V	10 W	30 D/V	30 D/V	30 D/V
4	10 W	30 D/V	30 D/V	30 D/V	10 W	30 D/V	30 D/V	30 D/V

During the tests, the aim point was maintained by small adjustments to the Universal Bearing Slide holding the weapon. The weapon and slide are shown in figure 3. When fired, the machine gun recoiled a short distance along the rails shown in the figure.

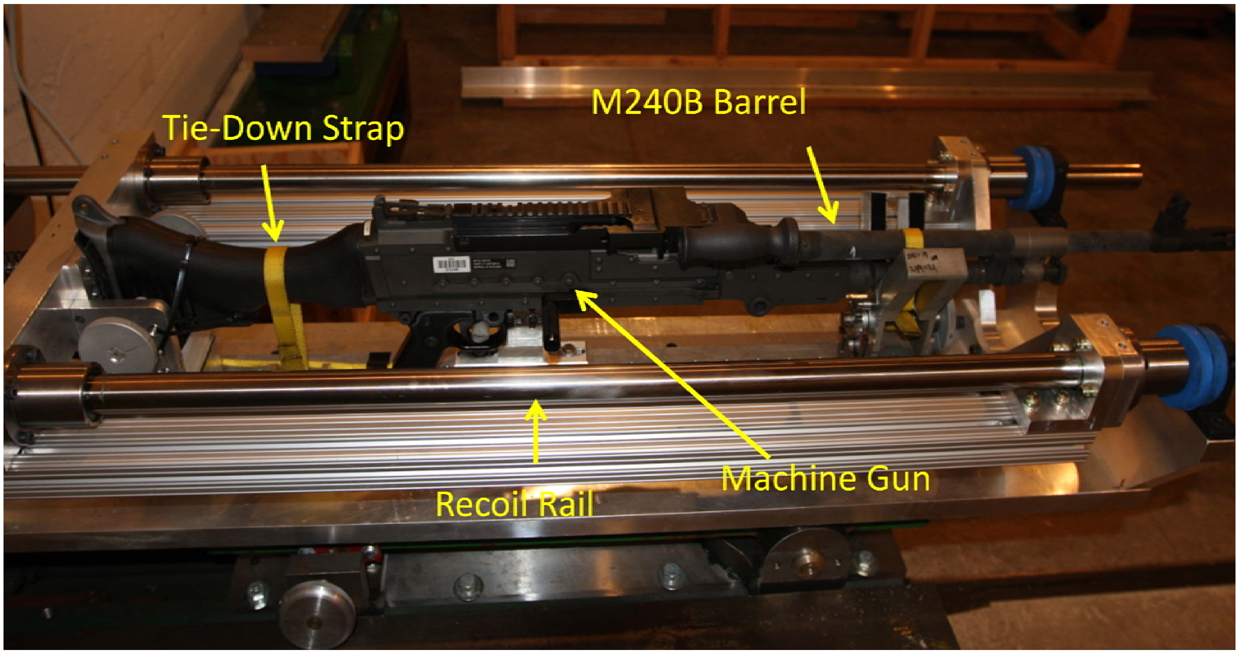

Figure 3. Weapon and universal bearing slide used for firings.

Commercially available HBN powder was obtained from Zyp Coatings (Oak Ridge, TN). The product comes in an aerosol can that can be used to spray the powder on the bullet. (An acetone/alcohol mixture is the powder vehicle.) The ammunition was coated with HBN by the use of a simple rotating device shown in figure 4. A motorized spindle is used to rotate the bullet while it is sprayed. The cartridge case was masked by a thin aluminum plate that rotates with the bullet. Only the leading portion of the bullet was coated. The fixture holding the bullet features a quick-hold, quick-release notch that allowed rapid insertion and extraction of the bullet. The spray time for each bullet was short, providing a thin but uniform coating. The ammunition was dried for 24 h before firing.

An Oehler 43 Chronograph System was used to measure the bullet muzzle velocity. Two light screens, located 120 in and 146 in from the gun muzzle determine time of arrival at the screen location. The velocities are computed and printed out for every 10-round group of shots.

A digitizer was used to measure the impact locations on each target.

After the tests, a 3 in piece of barrel was cut from barrel 1 at the muzzle. The piece was sectioned along its axis, and the surface of the bore was examined for traces of HBN with both a light microscope and an electron microscope.

Figure 4. Rotating device for coating ammunition with HBN.

2.2 Phase 2

Barrel 1 was chosen for adaption to the DM device. The original device, envisioned for the M240B barrel, had a length L between 3 and 4 in. These are arbitrary but reasonable dimensions, given the overall length of the barrel itself. Attention was first focused on the 3 in length, because it would have the lesser impact on the muzzle velocity. Figure 5 shows the dimensions of the barrel, as provided to the ARL shops. A 3 in length was cut from the end of barrel 1 and a thread length of 0.75 in was machined 1.25 in from the cut end. This allowed a centering section of 1.25 in at the end of the gun tube. A soft copper washer was placed at the end of the gun tube to enable the device to be screwed tightly to the end of the barrel. A slight ramp (not shown in figure 5) was machined into the DM device where it transitioned to the gun tube. The ramp inner diameter started at 0.300 in and ended at the bore diameter of the DM device ("a" in the figure). The DM device was made of high-strength tool steel, hardened (after machining) to HRC 60.

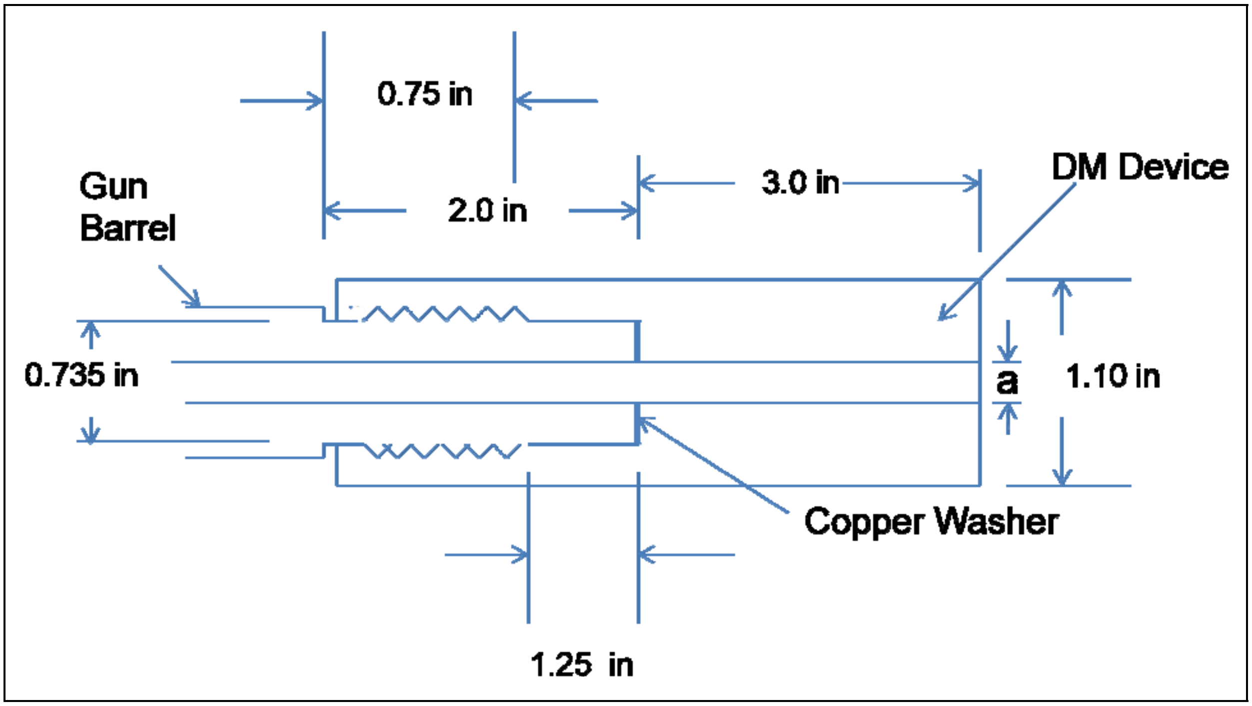

Figure 5. Cross-sectional schematic drawing of DM device with dimensions.

Two values of the DM device bore diameter were chosen: 0.2975 in and 0.2950 in. The tolerance was ±0.0005 in. The rationale for the choice of 0.2975 in for one of the bore diameters was that it afforded a minimal reduction in-bore diameter from the M240B barrel but was large enough to show an effect. The second choice was more aggressive.

The DM device with the 0.2975 in-bore diameter was attached to the end of barrel 1. Locktite* was applied to the threads to ensure a good lock between the device and the barrel.

The barrel with the device attached was fired in a range equipped with a Phantom High-Speed Video camera. Pictures of the bullet were taken just after it exited from the gun muzzle. As before, ammunition coated with HBN was fired. Because these firings were meant to see if the bullet could get through the constriction, only five shots were scheduled. After the first five shots, an attempt was made to unscrew the DM device. However, all attempts failed, and the second DM device was not fired.

Muzzle velocities were measured, and target impact points were recorded. Because only five shots were fired, a good measure of the dispersion was not obtained.

It was realized that the coating on the bullet would not likely influence the effect of the HBN on the muzzle velocity (see next section). Therefore, the tests were repeated with the barrel coated with HBN in the manner described in section 2.3. The same lot of ammunition was used for these tests.

*Locktite is a registered trademark of Henkel Corporation, Westlake, OH 44145.

2.3 Phase 3

The purpose of the third phase of the tests was to see if the dispersion and velocity were affected by the DM device. Barrel 2 was chosen for this phase. Based on the results of phase 2, a DM device with an inner diameter of 0.305 in (7.75 mm) was selected. The same tests as were conducted in phase 1 were repeated so that a comparison of performance could be made. (The same lot of ammunition was used for these tests.)

In this phase, the bullets were not coated with HBN. It was noted that the portion of bullet receiving the coating in the first two phases of the tests had little or no contact with the bore surface. Therefore, the transfer of HBN to the bore surface from the bullet would be minimal. In order to increase the effect of the lubricant, the bore surface and DM device were treated directly with HBN before firing. Barrel 1 was used as a test case, and the coating procedure was varied for this barrel. The procedures are summarized in table 2. In general, the lubricant was sprayed on the inside of the barrel and DM device. Next, a lead ball with diameter 0.33 in was inserted a short distance into the bore at the breech end. Another coating was sprayed behind the lead ball. After that, the lead ball was rammed through the bore and DM device with a brass rod. Several balls were used for both barrels 1 and 2. Note that barrel 2 was processed with two DM devices: one with a bore diameter of 0.295 in and the other with a bore diameter of 0.305 in. The table contains the measured values of the lead ball diameters after processing. These diameters are less than the original ball diameters and represent the amount of deformation resulting from the ramming process. (Note that the balls are grooved after processing, and the measurements are taken at the “land” location.)

Table 2. HBN processing parameters.

Barrel No.	Ball No.	DM Device Diameter (in)	Recovered Ball Diameter (in)	HBN Applications
1	1	0.2975	0.2970	One application
1	2	0.2975	0.2975	Not applied
1	3	0.2975	0.2975	Two applications before insertion; one after
2	4	0.305	0.305	Two applications before insertion; one after
2	5	0.305	0.305	One application before insertion; one after
2	6	0.2950	0.2955	One application before insertion; one after
2	7	0.2950	0.2955	One application before insertion; one after

In some instances, there was a noticeable decrease in the force needed to ram the second ball. It was also noted that on the first pass, there were regions where the force necessary to ram the lead ball was greater than in other regions, indicating a possible nonuniform bore diameter. The processing also resulted in coating the chamber of the gun tube with HBN. It was found that the HBN could not be removed by simply wiping the surface. In order to remove it, the surface had to be wiped with acetone.

The initial tests of barrel 2 had to be stopped due to misfires. It was suspected that the HBN coating of the chamber area was responsible. The HBN was removed from the chamber and the tests resumed. Problems were still encountered, and at that time range personnel noticed that the headspace was too large. This apparently resulted from the reassembly of the barrel after the machining process. The headspace was adjusted, and the tests were completed.

The one difference between tests conducted in phase 1 and those in phase 2 was that a separate target was used for each of the 10 shots in phase 2. This allowed a more accurate determination of shot location because the chance for bullet hit location to overlap was much smaller with the greater number of targets.

3. Results

3.1 Phase 1

The bore measurements taken with the BEMIS are actually averages of the bore diameters at the land location for each barrel. The barrels are virtually indistinguishable with respect to average bore diameter (figure 6).

The dispersion of each 30-round group was determined by first locating the center of the shot group. The standard deviation for each shot group was calculated and then divided by the distance to the target (307 ft) to obtain the dispersion value for that group. The group dispersion values for each barrel were then pooled to determine a geometric mean. The pooled dispersion values for the four barrels varied between 0.2 and 0.36 mils (table 3). Note that X stands for the horizontal component of the dispersion, and Y stands for the vertical component.

Each 30-round group was broken into three 10-round groups, and the Oehler 43 Chronograph System automatically generated the average velocity for each 10-round group. (The standard deviation for the 10-round groups was approximately 10 ft/s.) An average velocity was determined for each 30-round group from these values. Finally, these average values were averaged to determine the final average velocity for each barrel. The values shown in table 4 are slightly above the 2800 ft/s muzzle velocity quoted for this weapon (*6*). The difference may be due to the exact location where the velocity measurements were made and whether they were extrapolated back to the muzzle.

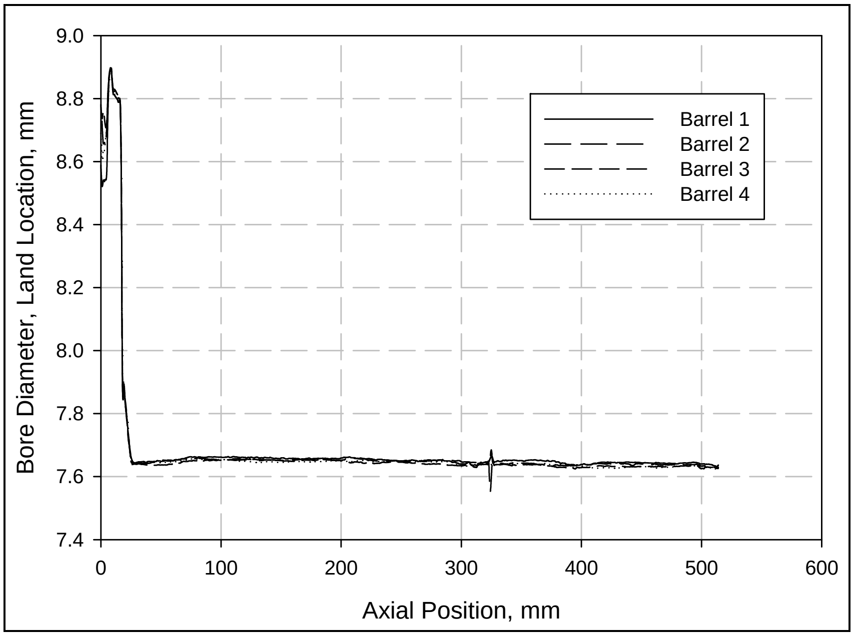

Figure 6. Average bore diameter at the land location for each barrel as a function of axial position.

Table 3. Pooled dispersion results.

Barrel No.	Standard Ammunition		Coated Ammunition	
	X Dispersion (mils)	**Y Dispersion (mils)**	**X Dispersion (mils)**	**Y Dispersion (mils)**
1	0.25	0.36	0.21	0.27
2	0.21	0.32	0.23	0.32
3	0.25	0.34	0.22	0.26
4	0.20	0.24	0.24	0.27

Table 4. Average velocities (ft/s) from phase 1.

Barrel No.	Standard Ammunition					Coated Ammunition				
	Group No.			**Overall Average**	**Std Dev**	**Group No.**			**Overall Average**	**Std Dev**
	1	**2**	**3**			**1**	**2**	**3**		
1	2788	2790	2785	2788	11.1	2817	2813	2820	2817	9.8
2	2819	2820	2818	2819	11.1	2816	2820	2822	2820	12.1
3	2816	2820	2823	2820	10.2	2820	2819	2825	2821	11.5
4	2812	2813	2820	2817	10.1	2808	2816	2819	2815	11.1

The velocity and dispersion results can be summarized as follows:

Dispersion:

1. All barrels fired with relatively low dispersion. Components of the horizontal dispersion were from 0.20 to 0.25 mils. Vertical components ranged from 0.24 to 0.36 mils. A good mass-produced rifle will have a dispersion of 0.3 × 0.3 mils; custom made rifles will have a dispersion much less than that.

2. There was no discernible difference in dispersion between standard and coated ammunition.

3. The vertical (Y) dispersion component was consistently greater than the horizontal (X) component.

4. There was no obvious trend toward lower dispersion with shot number for the coated ammunition.

5. Barrel 4 had a statistically significant lower dispersion than the other three barrels (*7*).

Velocity:

1. Except for the velocity results of the first barrel with standard ammunition, the observed average velocity for each shot group did not vary significantly from barrel to barrel for a given type of ammunition. The difference between the average velocity for barrel 1 with standard ammunition and the other averages cannot be explained at this time. All ammunition used in the tests was taken from the same lot, so lot-to-lot differences can be excluded. If an average is taken of all the average velocities (except barrel 1 with standard ammunition), it is found that the largest deviation of any one shot group from this average of averages is less than 0.5%.

    a. High-shot group: 2825 ft/s

    b. Low-shot group: 2808 ft/s

    c. Average of averages: 2817.8

    d. Largest deviation: 9.8 ft/s (0.3%) for fourth barrel, first shot group

2. There was no discernible difference between velocities of standard and coated ammunition.

3. There was no obvious trend toward higher velocity with increasing shot number for the coated ammunition

4. There was no discernible difference between the standard deviations for the coated and uncoated bullets.

A 3 in section was cut from barrel 1 at the muzzle end and sectioned to reveal the rifled surface. The surface was examined with a scanning electron microscope to see if HBN had been deposited there. A typical image is shown in figure 7. The small white globules less than 5 µm in diameter were identified by energy dispersive spectroscopy (EDS) as copper. There was no evidence that any HBN had been deposited on the barrel surface near the muzzle.

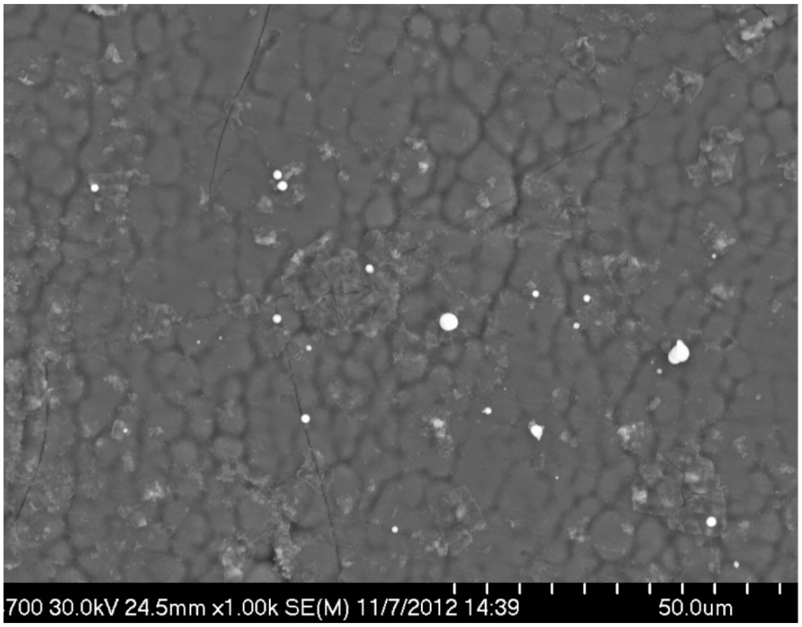

Figure 7. Scanning electron microscope image of bore surface of barrel 1.

3.2 Phase 2

The important result obtained from the second phase of testing was that the bullets emerged from the barrel intact. Figure 8 shows a picture of the bullet 4.056 ms after trigger pull. The bullet jacket is still attached to the core, and it appears to be flying straight (although with a little yaw).

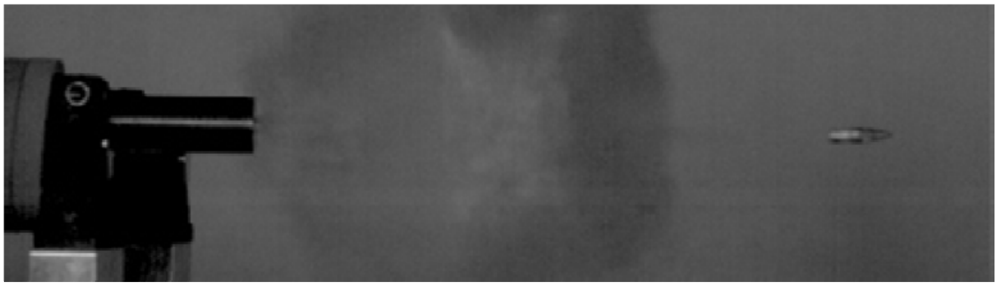

Figure 8. Picture of bullet in flight 4.056 ms after trigger pull.

The recorded velocities are shown in table 5 for both the initial five-shot group and the five-shot group that had the barrel and the DM device coated with HBN with an inner diameter of 0.2975 in. These values are approximately 100 ft/s lower than the baseline values (without the DM device). There did not appear to be any difference between the average velocity for the first and second five-shot groups. An overall average of the 10 shots was calculated to be 2711 ft/s.

Table 5. Velocities from phase 2.

Shot Group 1		**Shot Group 2**	
Shot No.	**Velocity (ft/s)**	**Shot No.**	**Velocity (ft/s)**
1	2697	1	2717
2	2705	2	2707
3	2707	3	2707
4	2692	4	2723
5	2737	5	2722
Average	2708	Average	2715
Std Dev	15.7	Std Dev	7.0

The bullet strike locations from phase 2 could not be used to provide an accurate determination of the dispersion. However, a qualitative examination of the target after firing the first five shots indicated that the dispersion was quite high (>1 mil for both X and Y).

3.3 Phase 3

The velocity and dispersion results for barrel 2 with the 0.305 in diameter DM device are shown in tables 6 and 7, respectively. The numbers were determined in exactly the same way the numbers shown in tables 3 and 4 were determined.

Table 6. Average velocities from phase 3.

	Group 1	**Group 2**	**Group 3**	**Average**
Muzzle velocity (ft/s)	2676	2784	2782	2778
Std Dev	18.5	14.6	13.4	—

Table 7. Phase 3 dispersion values.

Group 1		**Group 2**		**Group 3**		**Average**	
X	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**
0.399	0.348	0.354	0.425	0.320	0.416	0.36	0.40

The velocities measured were slightly lower than those without the DM device (2778 ft/s vs. 2818 ft/s). The dispersion was slightly higher with the DM device (0.36 by 0.40 mils vs. 0.21 by 0.32 mils).

Range personnel noted that the bore surface appeared to be cleaner than expected after firing over 100 rounds. Thus, there is a possibility that the use of HBN will reduce or prevent fouling of the barrel. Further studies are required to substantiate this possibility.

4. Discussion

The test program with the DM device has answered the questions first posed. Phase 2 of the program showed that a bullet could traverse a muzzle device with a reduced bore diameter and emerge intact. There will be a limit on the degree of constriction for this to happen, but, with a constriction of up to 3%, the bullet can survive launch.

The expectation that there would be an increase in muzzle velocity using the DM device was not met. In fact, the device decreased the muzzle velocity. The limited amount of data generated in this study can be used to show the relationship between the muzzle velocity and amount of constriction. A plot of the measured average muzzle velocity for barrel 2 without the device, barrel 2 with the device (0.305 in-bore diameter), and barrel 1 with the device (0.2975 in-bore diameter) is shown in figure 9. Over the limited range of constriction studied, the relationship is fairly linear. It is likely that the original muzzle velocity would be recovered using a DM device with a bore diameter of 0.308 in (gun bore diameter at the land location). However, that would have to be demonstrated with actual firings.

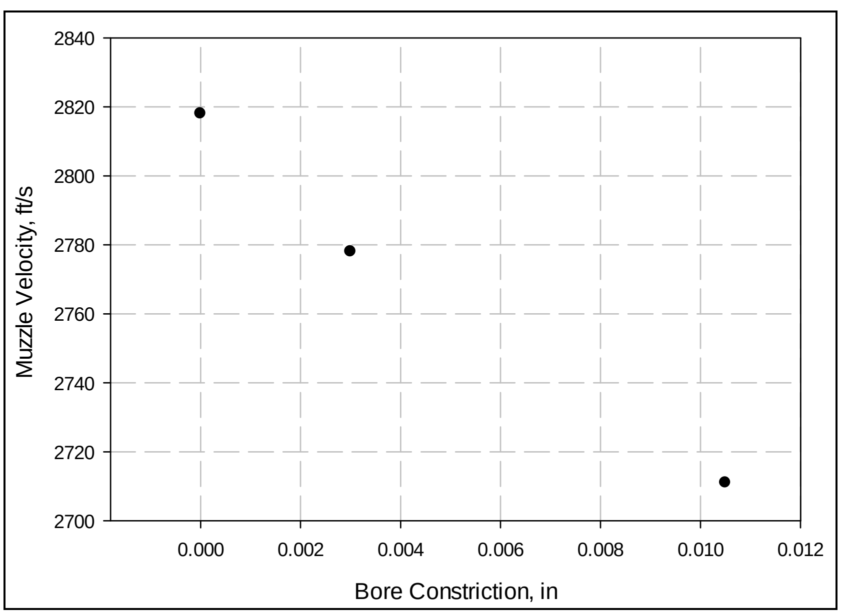

Figure 9. Muzzle velocity vs. bore construction.

Firing bullets coated with HBN did not change the muzzle velocity for the four barrels used in the study. However, a closer examination of the bullet geometry showed that little, if any, of the coating interacted with the bore surface. Consequently, the entire barrel and DM device were coated with HBN. The limited data generated with barrel 2 showed no difference in muzzle velocity with and without HBN. Even more importantly, use of HBN was not sufficient to overcome the increased frictional forces of the DM device on the bullet and recover the original muzzle velocity. The one positive result was that the bore surface appeared to be much cleaner than expected after firing over 100 rounds.

The role of HBN as an antifouling agent (and not as a lubricant) is consistent with results obtained in this study. Because a new chrome tube does not foul readily, the use of HBN would show no improvement. However, HBN as an antifouling agent could make a difference in an unchromed, low-alloy steel barrel and might explain the results seen by Caulkins (*4*). More scientific investigation is required to settle this issue.

Dispersion increased using the DM device. The amount of increase is likely associated with the degree of constriction. However, even with a DM device having the same bore diameter as the gun tube diameter, there is an additional interface the bullet must traverse as it exits the muzzle. This may be an additional source of dispersion so that, even if a DM device with the same bore diameter as that of the gun tube was used, it might still result in increased dispersion. The vibration characteristics of the gun tube and DM device are different from those of the original gun tube, which may be an additional source of increased dispersion.

5. Conclusions

Tests have been conducted on a muzzle device intended to reduce muzzle wear and increase the accuracy of a gun tube over its entire service life. It consisted of an attachment to the end of the gun tube that was made of a hard material that could resist wear better than the gun steel used for the barrel. As envisioned, the device had a bore diameter slightly smaller than the bore diameter of the gun tube. The constricted bore diameter of the device was intended to reduce or eliminate the yaw of the bullet as it left the gun tube. This could lead to a lower dispersion. In addition, there was the possibility that by slowing the bullet down before it left the gun tube, more time would be given for propellant to burn inside the gun tube, resulting in higher pressure/higher muzzle velocity and reduced muzzle blast. In fact, the tests showed that the device reduced the muzzle velocity and increased the dispersion. However, with a design that had the same bore diameter as the gun tube, it is expected that the original values of muzzle velocity would be recovered, and that its wear-resisting properties would, during the latter stages of the service life of the tube, provide reduced dispersion as compared to a gun tube without the device.

6. References

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5. Boyle, P.; Humphrey, A.; Courtney, M. *Quantifying Friction Effects of Molybdenum Disulfide, Tungsten Disulfide, Hexagonal Boron Nitride, and Lubalox as Bullet Coatings*, U.S. Air Force Academy Research Report, July 2012.

6. M240 Family of Medium Machine Guns, FN Manufacturing, LLC, Columbia, SC, October 2006.

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Appendix. Sources of Dispersion

Rifle precision can be quantified by the amount of dispersion a given rifle produces. That is, given an aim point, how close does the bullet come to hitting the aim point? Dispersion is generally measured by firing a set number of rounds at a fixed target and then measuring the miss difference of each bullet from the aim point. The standard deviation of these miss differences, divided by the gun-to-target distance, then constitutes the dispersion. Clearly, the lower the dispersion, the more precise the given rifle is.

There are many reasons why the bullet does not hit the aim point precisely. Most of these reasons are covered in reference 1.[1] The following list is taken from this reference but is not all-inclusive:

1. Barrel manufacturing precision

   Examples: barrel smoothness, barrel straightness, barrel residual stress, chamber finish, chamber concentricity, neck diameter, neck concentricity, throat length, throat concentricity, and proper bore and groove diameter

2. Barrel vibration (caused by recoil forces and firing pin impact)
3. Scope sight motion (aiming error)
4. Barrel joint motion
5. Muzzle blast effects, combined with canted bullets
6. Bullet core problems
7. Bullet imbalance
8. External ballistic problems (effects of wind, temperature, air density, etc.)
9. Bore fouling and surface conditions

Dispersion can be reduced through use of high-precision manufacturing practices. For instance, if the identical powder load can be used in each round of ammunition, then variation in muzzle velocity will be reduced, also reducing the error associated with variations in the trajectory drop due to gravity. The same can be said for bullet mass. However, higher precision means higher production costs. Therefore, there will always be a tradeoff between cost and desired precision, especially when it comes to mass-produced weapons made for the armed services.

The effects of the environment (temperature, wind velocity, humidity, etc.) can be reduced or eliminated by firing in an indoor test range. This will help determine the inherent dispersion characteristics of the ammunition-weapon system. Similarly, effects of bore fouling can be reduced through frequent barrel cleaning.

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[1] Vaughn, H. R. *Rifle Accuracy Facts*; Precision Shooting: Manchester, CT, 1998.

There are other causes of imprecision in the above list that can be overcome with some effort. These would include barrel vibration, muzzle blast effects, bore fouling, and exterior ballistics. Another possible cause of increased dispersion in this category (not listed above) is muzzle wear. Vaughn[1] indicates how, by redesign of the weapon, barrel vibration and its effect on dispersion can be reduced. Similarly, use of a vented muzzle will reduce muzzle blast effects. Finally, the proposed DM device is intended to eliminate barrel muzzle wear effects.

Vaughn[1] demonstrated that certain small caliber bullets could be canted in-bore, leading to increased dispersion. A canted bullet is one whose longitudinal axis is at an angle to the centerline of the bore. Because a bullet fired through a rifled barrel will rotate inside the barrel as it travels towards the muzzle, the three-dimensional path of the nose is in the shape of a cork screw. The bullet axis, as projected onto a vertical plane parallel to the gun bore, will oscillate up and down as it proceeds down the bore. This two-dimensional motion has often been called "balloting."

The degree of bullet cant depends on its design. Figure A-1 shows the cross section of a small caliber bullet. The front portion of the bullet features a tangent ogive nose, followed by the afterbody. The afterbody may be tapered, cylindrical, or a combination of both. The cylindrical section provides the bearing surface. In general, afterbodies that have long bearing surfaces will be less prone to canting than those with short bearing surfaces.

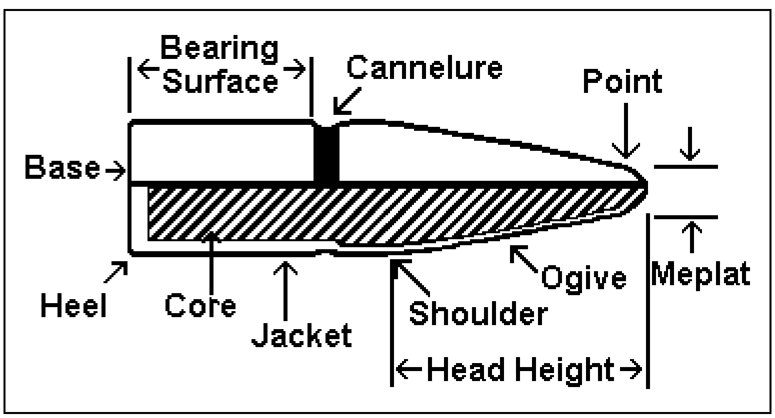

Figure A-1. Cross section of the surface of a generic small caliber round of ammunition.

The cant angle is determined in the first few calibers of bullet travel. This can be due to improper seating of the cartridge in the chamber, excessive wear at the origin of rifling, or a combination of both. Vaughn[1] estimated from recovered bullets that the tapered afterbody of a commercially available hunting round (90 grain 0.270 Win bullet) would allow a cant angle of 0.5°. The M80 (7.62 mm) round of ammunition has an afterbody with a cylindrical section that is 3.91 mm (0.154 in) long. (The entire length of the bullet is 28.4 mm.) The diameter of this cylindrical section is 7.82 mm (0.308 in). The inner diameter of a 7.62 mm weapon is 7.82 mm (0.308 in) at the groove location. During a firing event this diameter will expand slightly due to the propellant

gas pressure. Near the breech where the pressure is the highest, the expansion could be on the order of 0.0005 in (0.5 mil), based on standard equations of elasticity.[2] However, setback forces on the bullet also expand it. The expansions would affect only a short portion of the rear of the bullet, leaving most of the cylindrical portion of the afterbody in contact with the barrel wall. In this case (M80 ammunition) it seems reasonable to assume that if the bullet enters the origin of rifling in a canted position, the tight fit between the rear of the bullet and the barrel wall will tend to reduce that angle, possibly to zero.

This cannot be said of a worn rifle barrel, however. There are two main areas where wear is the greatest: the throat of the barrel, where thermo-chemical-mechanical effects erode the bore surface, and the muzzle end of the barrel, where mechanical wear is the greatest. It can be argued that wear at the muzzle may affect the dispersion the most, because barrel vibration and muzzle blast effects may be enhanced by a poor fit between the bullet and the barrel. There is also the possibility that increased blow-by of propellant gasses will tip the bullet in a random direction before the bullet exits the barrel.

Given that the length of the bearing surface of the bullet is L, its diameter is d, and the barrel diameter at the groove location is D, it can be shown (in an idealized geometry) that

$$D = d\cos\alpha + L\sin\alpha\,, \tag{A-1}$$

where α is the maximum possible cant angle. When there is no wear, the cant angle is zero. For small values of the cant angle, α can be found as a function of D:

$$\alpha = 6.52D - 2.008\,, \tag{A-2}$$

where α is in radians. This equation applies to the 7.62 mm rifle. If there is a uniform wear of 0.002 in, then D = 0.31 in and the maximum possible cant angle is 0.0132 rad (0.75°).

These points argue for the use of the DM device, which will eliminate or reduce greatly the extent of mechanical wear at the muzzle of the gun tube.

[2]Timoshenko, S., *Strength of Materials, Part II: Advanced Theory and Problems*; D. Van Nostrand Company, Inc.: New York, 1953.

List of Symbols, Abbreviations, and Acronyms

ARL	U.S. Army Research Laboratory
BEMIS	Bore Erosion Measurement and Inspection System
DM	de Rosset−Montgomery
EDS	energy dispersive spectroscopy
HBN	hexagonal boron nitride
HRC	Rockwell Hardness C Scale

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